

Deep Caribbean Sea warming

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12 **Abstract**

13 Data collected from hydrographic stations occupied within the Venezuelan and
14 Columbian Basins of the Caribbean Sea from 1933 through 2003 are analyzed to study
15 the decadal variability of deep temperature structure in the region. The analysis is limited
16 to waters below 2000 dbar, a bit deeper than the 1815-m sill depth of the Anegada –
17 Jungfern Passage through which relatively dense (compared to abyssal Caribbean water)
18 water from the North Atlantic enters to ventilate the deep Caribbean Sea. Warming at a
19 rate of about $0.01\text{ }^{\circ}\text{C decade}^{-1}$ below this sill depth appears to have commenced in the
20 1970's after a period of relatively constant deep Caribbean Sea temperatures extending
21 back to the 1930's. CTD station data from WOCE Section A22 along 66°W taken in
22 1997 and again in 2003 provide an especially accurate estimate of this warming over that
23 6-year period. They also suggest a small (0.001 PSS-78 , about the size of expected
24 measurement biases) deep freshening. The warming is about 10 times larger than the size
25 of geothermal heating in the region, and is of the same magnitude as the average global
26 upper-ocean heat uptake over a recent 50-year period. Together with the freshening, the
27 warming contributes about $0.012\text{ m decade}^{-1}$ of sea level rise in portions of the Caribbean
28 Sea with bottom depths around 5000 m.

29 *Keywords:* Caribbean Sea; Climate Change; Sea Level Rise; Ocean Warming

30

1. Introduction

The ventilation of the main deep basins in the Caribbean Sea, the Venezuelan and Columbian Basins, is accomplished through an inflow of relatively dense water of North Atlantic origin through the Anegada – Jungfern Passage (Sturges, 1975; Stalcup et al., 1975; Fratantoni et al., 1997; MacCready et al., 1999). The rate of deep inflow into the Caribbean inferred from hydrographic measurement and current meter measurements near and downstream of the passage is around $0.05 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (Sturges, 1975; Stalcup et al., 1975), whereas the rate inferred from a box model using ^{14}C data is over $0.2 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ (Ribbat et al., 1976). The larger value of transport has been quoted in the more recent literature (Joyce et al., 1999; Johns et al., 2002).

Since the controlling sill depth of the Anegada – Jungfern Passage is about 1815 m (Stalcup et al., 1975), the waters below that depth in the Caribbean Sea generally tend to be relatively homogenous in water properties both vertically and horizontally, all throughout the Venezuelan and Columbian Basins (Ribbat et al., 1976). The exception to this rule is downstream of the Anegada – Jungfern Passage, where plumes of relatively cold, salty, silic acid-poor, and oxygen-rich water can be found descending into the Venezuelan Basin (Sturges, 1975, Stalcup et al., 1975).

Potential temperatures profiles in the deep Venezuelan Basin were apparently relatively time-invariant in the 1930's, 1950's, and 1960's, with values approaching as cold as $\theta = 3.80 \text{ }^\circ\text{C}$ near 5000 m during those decades (Worthington, 1966). However, a comparison of data in the Caribbean Sea from a 1958 IGY section nominally along 66°W with more recent data from the 1997 WOCE hydrographic section A22 along the same

nominal longitude finds a statistically significant warming of $\Delta\theta = 0.041$ °C (along with a statistically insignificant freshening of $\Delta S = -0.0016$ PSS-78 in salinity) between 1958 and 1997 (Joyce et al., 1999). The differences are approximately constant in the vertical from about the sill depth of 1800 m to the bottom. Joyce et al. (1999) attributed this change to a long-term warming of the deep waters of the North Atlantic (Joyce and Robbins, 1996) that ventilate the deep Caribbean.

In 2003, WOCE section A22 was reoccupied as part of the U.S. Repeat Hydrography Program in support of CLIVAR and CO₂ studies. Here a comparison of the 2003 and 1997 data is presented, demonstrating continued warming in the deep Caribbean Sea, and perhaps slight freshening as well in the latest interval. In addition, an analysis of historical temperature profiles from the World Ocean Database 2005 (Boyer et al., 2006) is in agreement with previous results (Worthington 1966) that deep Caribbean Sea temperatures were steady from the 1930's through the 1960's, and in fact into the 1970's, with detectable warming commencing only in the 1980's and continuing through 2003.

2. Data

In August 1997 high-quality CTD station data were taken in the Caribbean Sea from the surface to the bottom as part of the occupation of WOCE Section A22, along nominal longitude 66°W. The stations were occupied at nominal horizontal spacing of 55 km, closer over rapidly varying bathymetry. Accuracies are thought to be 0.002 °C for temperature, 0.001 PSS-78 for salinity, and 2 dbar for pressure (Joyce et al., 1999). In 2003, the U.S. Repeat Hydrography Program reoccupied this section in support of CLIVAR and CO₂ science, crossing the Caribbean in October of that year. Accuracies of

CTD data are thought to be similar to those in 1997 during the 2003 survey (<http://cchdo.ucsd.edu>). Standard Sea Water (SSW) batch P131 was used to standardize the salinity measurements in 1997, and SSW batches P140 and P141 were used to standardize the salinity measurements in 2003. Following Kawano et al. (2006), +0.0001 PSS-78 is added here to the 1997 salinity data and -0.0003 to the 2003 salinity data to account for differences among the SSW batches used.

Additional deep historical temperature profiles in the Caribbean Sea (Fig. 1) are obtained from the World Ocean Database 2005 (Boyer et al., 2006). Only data with good quality flags are used in this analysis. Stations are limited to those south of 17°S within the 2000-m isobath of the Venezuelan and Columbian Basins with more than 3 temperature measurements below 2000 dbar. Depth data are converted to pressure using the standard equation, and potential temperatures are estimated using the temperature and pressure data assuming a salinity of 34.98 PSS-78 (a value typical of the Caribbean Sea below 2000 dbar). Further screening of historical station data is accomplished by fitting potential temperature profiles for each station as an exponential function of pressure below 2000 dbar (Fig. 2). Stations with any parameter of the fit that is 1.5 times the interquartile range greater than the third quartile or less than the first quartile are discarded, as are stations where the standard deviation of the fit residual exceeds 0.02°C. This threshold is about the magnitude of the expected accuracy of historical temperature data from Nansen bottle casts. After this screening, 135 historical stations remain between 1933 and 2003, including 9 stations from the 1997 occupation of WOCE Section A22 and another 9 stations from the 2003 reoccupation (Fig. 1).

3. Repeat section analysis

The most accurate estimates of property changes in the deep Caribbean Sea are probably afforded by closely spaced full water-column repeat CTD sections such as the 1997 and 2003 repeats of WOCE Section A22. Following Joyce et al. (1999), the analyses of these data are carried out in pressure coordinates between 12.5 and 16.5°N. The potential temperature and salinity data for each station are low-passed vertically with a 40-dbar half-width Hanning filter. The results are then interpolated to a 10-dbar-pressure grid. The vertically gridded data sets are then interpolated onto an evenly spaced latitudinal grid at 2' spacing using a space-preserving piecewise cubic Hermite interpolant at each pressure (and σ_4) level. This spacing matches that of a high-resolution bathymetric dataset used here generated by merging satellite altimetry data with bathymetric soundings (Smith and Sandwell 1997). The bathymetry from this dataset along each section is used as a mask to eliminate data that have been interpolated to locations below the ocean.

The differences of these two gridded fields are averaged at each pressure level within the specified latitudes (Fig. 3). The 95% confidence limits for the mean differences are estimated following Johnson et al. (2008). First integral spatial scales for each quantity studied at each pressure level are estimated from integrals of autocovariances (e.g. Von Storch and Zwiers, 2001) in latitude. The effective numbers of degrees of freedom are then computed by dividing the latitude ranges sampled at each pressure level by the appropriate integral spatial scales. These effective degrees of freedom are used throughout the error analysis, including application of Student's t-test for 95% confidence limits.

The warming rate below the 2000 dbar is essentially constant at about $+0.010^{\circ}\text{C}$ over the 6.2-year interval between the repeat occupations (Fig. 3). This result is highly significant in a statistical sense. There also appears to be about 0.001 PSS-78 in freshening between 1997 and 2003 (Fig. 3). While this result is statistically significant, the accuracy of each cruise is about 0.001 PSS-78, so it is possible that salinity measurement biases between the two cruises could be the source of this difference.

4. Historical data analysis

As mentioned in Section 2, 135 historical stations (including the WOCE and CLIVAR occupations of WOCE section A22) pass a set of screening criteria (Fig. 1). The data from these stations, linearly interpolated in the vertical to a uniform pressure grid between data locations, are used to explore the temporal evolution of deep temperatures in the Caribbean Sea. It is assumed that there is little spatial variability of temperature profiles in the Venezuelan and Columbian Basins (Ribbat et al., 1976). While there are a few stations that pass the screening criteria in the 1930's, it is not until the 1950's that sufficient data exist to construct decadal mean profiles of vertical temperature in the deep Caribbean (Fig. 4). The 1950's, 1960's, and 1970s mean vertical profiles of potential temperature versus pressure are somewhat noisy and overlap in places. However, the 1980's mean curve appears warmer than those for the previous three decades by about 0.01°C throughout much of the water column below 2000 dbar, and that pattern continues into the 1990's and 2000's.

The time-history of historical data on the 3000-dbar isobar (Fig. 5) allows another look at this pattern. No change evident within the variability (shown as standard

deviations) of the decadal means of temperature data in the 1930's, 1950's, 1960's, and 1970's. However, the 1980's appear to be warmer than previous decades. Furthermore, clearly statistically significant warming occurs between the 1980's and the 1990's, and the 1990's and the 2000's. In short, the abyss of the Caribbean appears to have been warming since the 1970's at an apparently steady rate of about $0.01\text{ }^{\circ}\text{C decade}^{-1}$.

5. Discussion

The rate of warming of the abyssal Caribbean below 2000 dbar between 1997 and 2003 from 12.5 to 16.5°N implies a heat gain of about 0.6 W m^{-2} along the section in that latitude range. This amount is considerably more heat than the 0.07 W m^{-2} estimated for geothermal heating at the bottom (Clark et al., 1978). In fact, this regional rate of deep heat storage increase exceeds estimates of global heat uptake from the surface to 3000 m over the past 40 years (Levitus et al., 2005). However, the deep Caribbean is only a small part of the global ocean volume, so the contribution of this warming to the global heat budget is relatively small on its own.

Assuming a constant deep salinity in the Caribbean, the warming below 2000 dbar between 1997 and 2003 accounts for thermosteric sea level rise at a rate of about $0.008\text{ m decade}^{-1}$ over regions of the Caribbean Sea with bottom depths around 5000 m. The rate would be smaller in shallower regions. If the slight freshening of 0.001 PSS-78 over the 6-years is real, adding the halosteric effect of that change to the sea level rise budget below 2000 dbar would increase the rate to about $0.012\text{ m decade}^{-1}$ in the deeper parts of the Caribbean Sea. This rate of change is a significant fraction of the total rate of global sea level rise of $0.03\text{ m decade}^{-1}$ since 1993 (Nerem et al. 2006), so at least in the

Caribbean, the bottom half of the ocean is a significant contributor to sea level rise budgets.

The cause of this abyssal Caribbean warming (and perhaps freshening) since the 1970's is an interesting question. Based on steady warming observed between 1500 and 2500 dbar from the 1920's through at least 1990 in an extended analysis of an ocean time-series at Bermuda (Joyce and Robbins, 1996), Joyce et al. (1999) suggested that the source waters entering the deep Caribbean through the Anegada – Jungfern Passage had warmed, thus warming the abyss.

Starting in the mid 1990's, on isopycnals characteristic of Labrador Sea Water (LSW), relatively cool, fresh, CFC-rich waters formed starting in 1988 during a period of vigorous convection that continued through 1996 (Yashayaev, 2007) began to arrive in the Deep Western Boundary Current (DWBC) off Abaco at 26.5°S (Molinari et al., 1998) and shortly thereafter off French Guiana at 7°N (Freudenthal and Andrié, 2002).

Presumably it is LSW within the DWBC that feeds the abyssal Caribbean through the Anegada – Jungfern Passage, and one might think that the reported cooling and freshening on isopycnals should be reflected in the differences in abyssal Caribbean temperatures between 1997 and 2003. However, just because the water cooled and freshened on isopycnals does not mean that it cooled and freshened on isobars near the 1815-m sill depth of the passage. The isopycnals in the North Atlantic near the sill of the passage could have deepened sufficiently in recent times so that even as water cooled and freshened on them to still feed warmer water into the deep Caribbean. In addition, the relatively long residence time in the deep Caribbean Sea of about 150 years probably also filters out decadal variations in the temperatures of the source waters its abyss (Joyce et

al., 1999), making deep temperature structure in the Caribbean Sea an indicator of longer-term changes in the characteristics of North Atlantic Water in the vicinity and near the sill depth of the Anegada – Jungfern Passage.

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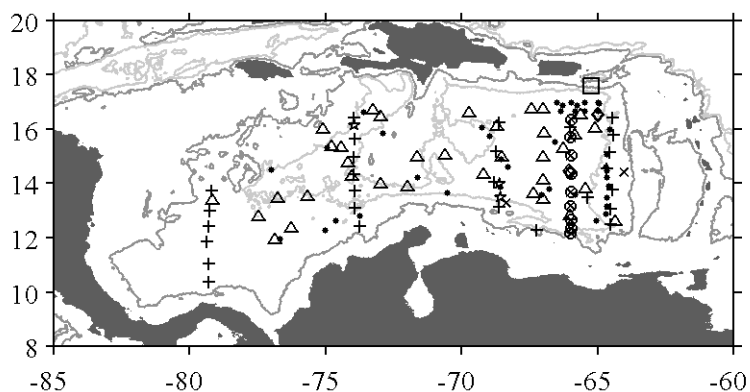
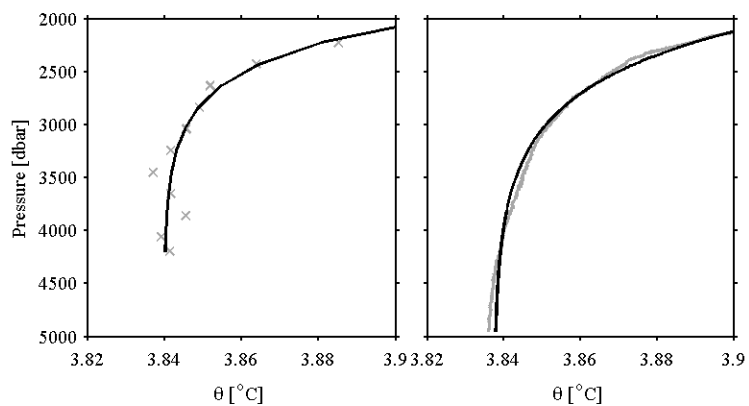


Fig. 1. Locations of hydrographic station data used in this analysis of deep property changes in the Venezuelan and Columbian Basins of the Caribbean Sea from the 1930's (pentagrams), 1950's (plusses), 1960's (dots), 1970's (triangles), 1980's (diamonds), 1990's (crosses), and 2000's (circles). The 2000-m (dark gray line) and 4000-m (lighter gray line) isobaths are contoured and a box is plotted over the 1815-m sill of the Anegada – Jungfern Passage. The 135 stations shown, including 9 each from the 1997 and 2003 occupations of WOCE section A22 along 66°W, passed a set of screening criteria described in the text.



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263 Fig. 2. Typical examples of exponential fits (dark lines) to hydrographic station data

264 (light crosses, left panel) and CTD station data (light line, right panel) within the deep

265 Caribbean Sea.

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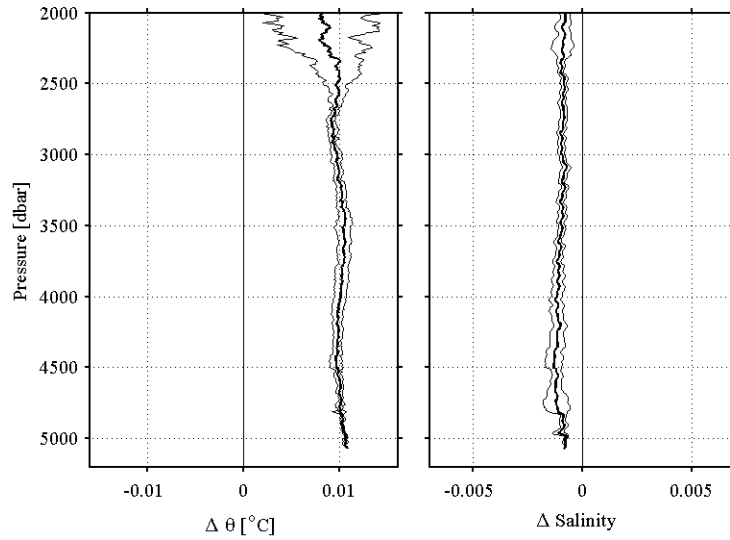
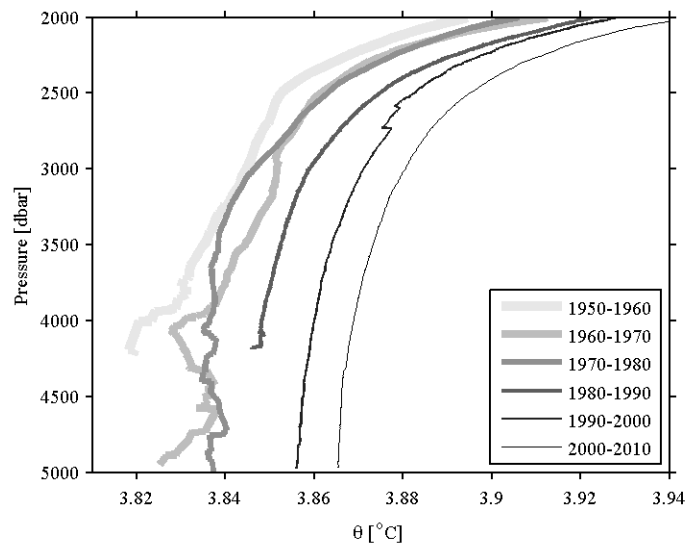


Fig. 3. Mean differences of potential temperature (left panel, black line), and salinity (right panel, black line) with 95% confidence intervals (grey lines) computed by subtracting 1997 data of WOCE section A22 along 66°W gridded against pressure and latitude from 12.5 to 16.5°N from the similarly gridded 2003 section data and then taking the latitudinal average as a function of pressure. Estimation of confidence intervals is described in the text.



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274 Fig. 4. Mean potential temperature profiles from screened historical data in the
 275 Caribbean Sea linearly interpolated as a function of pressure averaged by decade from the
 276 1950's through the 2000's.

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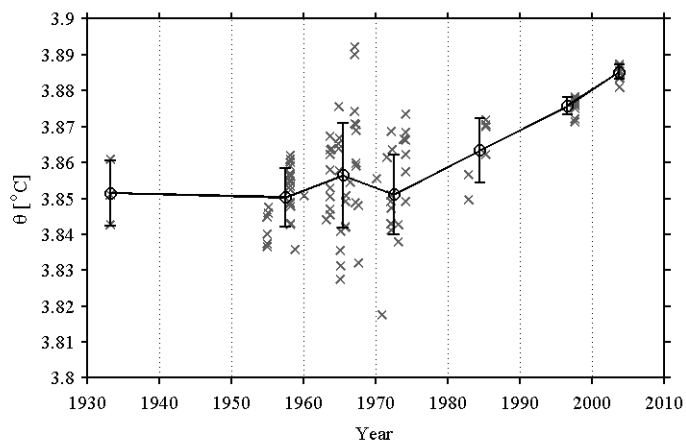


Fig. 5. Potential temperature profiles from screened historical data in the Caribbean Basin linearly interpolated to 3000-dbar pressure (crosses). Average potential temperature values plotted at the average station time for each decade (circles connected by solid line) with one standard deviation potential temperature error bars for each decadal average.